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The hidden indirect environmental effect undercuts the contribution of crop nitrogen fertilizer application to the net ecosystem economic benefit

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ABSTRACT

The current environmental and economic challenges of the application of nitrogen (N) fertilizer on crops are not only to provide an adequate food supply but also to reduce the resulting environmental pollution. A comprehensive understanding of the multiple effects of N fertilizer application on crops will help to more accurately guide the application of N fertilizer to meet current challenges, and to promote sustainable crop production. It is widely known that excessive N fertilizer applied to crops can lead to N-related direct environmental effects, including reactive N (Nr) losses, greenhouse gas emissions, and high environmental costs. However, few studies have revealed the hidden indirect environmental effect of crop N fertilizer application and its impact on the net ecosystem economic benefit (NEEB), which may be triggered by a N-crop-pest cascade pathway. In this study, we conducted three-year wheat field experiments at five N fertilizer application rates (0, 70, 140, 210, and 280 kg ha^{-1}) in a city on the North China Plain. Excluding wheat yield and direct N-related environmental effects, the indirect effects of N fertilizer application, including the occurrence of cereal aphids (the most important wheat insect pests), the use of chemical pesticides for pest control, the impacts on the environmental and human health damage costs and NEEB were studied. Our results showed that the abundances of cereal aphids positively correlated with the N fertilizer application rates. At each N fertilizer application rate (70, 140, 210, 280 kg ha^{-1}), 0.447 kg of active ingredients of chemical pesticides (0.222 kg insecticides and 0.225 g fungicides) per hectare per season were used to control insect pests and pathogens, while no pesticides were used at 0 kg ha^{-1}(i.e., no N fertilizer was applied). The environmental and human health damage costs of pesticides for pest control increased $8 per hectare for wheat at four N fertilizer application rates and then reduced NEEB by the same amount. Our work extends previous studies and reveals the indirect negative environmental effect of N fertilizer application on crops triggered by a N-crop-pest cascade pathway. This effect undercuts the contribution of crop N fertilizer application on NEEB.

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1. Introduction

Excessive amount of nitrogen (N) fertilizer have been used to meet the nutritional demands of the crops and to increase their yield and make a major contribution to food production (Erisman et al., 2007; Tilman et al., 2002). However, excess N remaining in the soil enters bodies of water through leaching and runoff or volatilizes into the air in the form of ammonia and nitrous oxide (Chen et al., 2014; Galloway et al., 2008; Matson et al., 1998), which causes serious environmental problems and threatens biodiversity and mankind's health (Christopher and Tilman, 2008; Guo et al., 2010). Making matters worse, the occurrences of most insect pests and pathogens on multiple crops increase along with the increase of N fertilizer application (Altieri and Nicholls, 2003; Gao et al., 2017; Luo et al., 2021; Rashid et al., 2017; Zhao et al., 2015). However, it is neglected that the indirect environmental effect of using insecticides for controlling abundant pests and pathogens resulting from the excessive application of N fertilizer to crops are being neglected (Fig. 1) (Martinez et al., 2021). The net ecosystem economic benefit (NEEB) is often used to assess the costs of crop production, agricultural activity, and the costs of environmental and human health damage (Cai et al., 2023; Zhang et al., 2015b; Zhou et al., 2019). However, nearly none studies have considered the indirect environmental effect of crop N fertilizer application triggered by a N-crop-pest cascade pathway and the impact of this effect on NEEB. Revealing this effect, the formation pathway of this effect and the impact of this effect on NEEB are beneficial for comprehensively recognizing the multiple effects of crop N fertilizer application and then improving N fertilizer management to increase the sustainability of agriculture (Loos, et al., 2014; Garnett and Godfray, 2014; Tilman et al., 2002).

The agronomic effects (e.g., yield and N use efficiency); the direct environmental effects, including N-related emissions from soil (e.g., N_2O, NH_3, NO_x, and nitrate leaching); and their formation pathways have been widely reported from local to worldwide scales (Cui et al., 2014; Erisman et al., 2007; Liu et al., 2016; Robertson and Vitousek, 2009; Sutton et al., 2011; Wang et al., 2017). N is an essential element for crop growth, and crop yields increase significantly after large amounts of N fertilizer are applied (Ladha et al., 2005; Zhang et al., 2015a). Therefore, crops in most parts of the world are gradually being treated with large amounts of N fertilizer, which has significantly increased crop yields and total yields in these regions (Zhang et al., 2015a). However, researchers havegradually discovered that after a large amount of N fertilizer is applied to crops, the yield does not increase indefinitely but instead remains stable after increasing to a certain level (Cerrato and Blackmer, 1990; Liu et al., 2016; Ju et al., 2009). Moreover, at both regional and global scales, as the amount of N fertilizer applied to crops increases, N use efficiency decreases significantly (Cui et al., 2014; Zhang et al., 2015a). This N unabsorbed by crops mainly enters the environment through three pathways (Fig. 1). First, it is leached or remains in the soil in the form of inorganic N such as nitrate N (Ma et al., 2019; Wang et al., 2017). Second, it is emitted into the air in the form of N oxides, such as nitrous oxide and ammonia (Cui et al., 2014; Matson et al., 1998). Third, it flows into bodies of water in the form of inorganic N, such as nitrate N (Cui et al., 2014). Due to the excessive application of N fertilizer to crops, many studies have reported that a large amount of Nr is released into the environment through the three pathways above on a national or global scale (Chen et al., 2014; Galloway et al., 2008), which has caused the loss of biodiversity and serious threats to human health (Christopher and Tilman, 2008; Davidson, 2009). Moreover, the accounting of environmental and human health damage costs of N fertilizer application has shown that the direct environmental effects of excessive N fertilizer application to crops significantly reduce the economic benefit of increased yields (Cai et al., 2023; Zhang et al., 2016b).

However, few studies have revealed the indirect effects of crop N fertilizer application and the formation pathway of these effects, as well as the impact of these effects on NEEB under different N application rates. The increased crop N content fromthese excessive N application increased the performances of crop pests and pathogens by relieving any constraints on their growth and reproduction due to the limitations of available protein (Martinez et al., 2021; Mattson, 1980), which results in outbreaks of insect pests and pathogens in multiple crops, including rice and wheat, among others (Han et al., 2019; Luo et al., 2021; Mahfuza and Gordon, 2008; Rashid et al., 2017). Farmers have the habit of "the more pests there are, the more pesticides are sprayed" (Chèze et al., 2020). A reduction in choice availability of synthetic insecticides translates in reduced confidence in the ability to effectively control insect pests (Bakker et al., 2021). More insect pests and pathogens occurred at excessive N rates leads to more spraying of chemical pesticides on crops (Hu et al., 2022; Martinez et al., 2021). This action futher aggravates the problems of environmental pollution, including more insecticide residues in agricultural soils, runoff into streams, and evaporation of the leaf/soil deposits (Fig. 1) (Bedos et al., 2002; Ippolito et al., 2015; Silva et al., 2019; Stehle and Schulz, 2015). The pesticides' environmental pollution results in many environmental and human health damage costs: pesticides in sources of drinking water, pollution incidents, fish deaths and monitoring costs, biodiversity/wildlife losses, acute effects of pesticides to human health and others (Leach and Mumford, 2008; Pimentel, 2005). However, when past studies

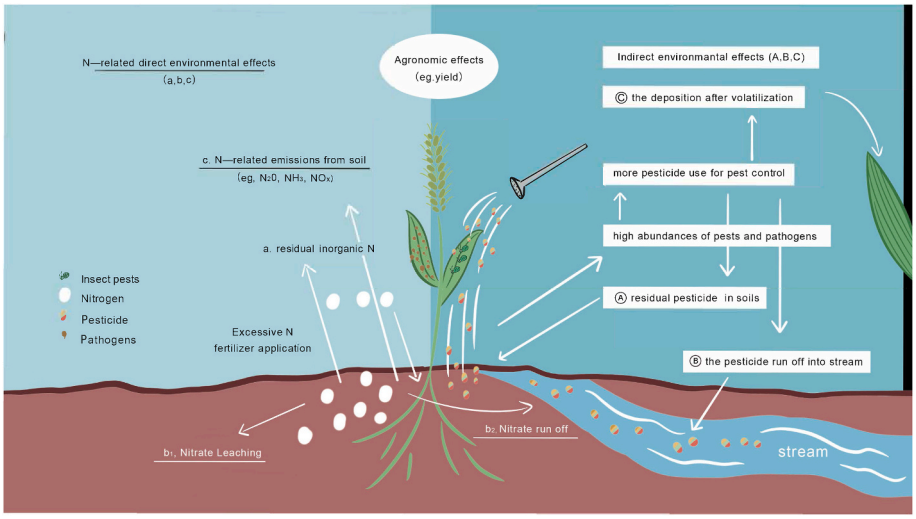

Fig. 1. Schematic diagram of the multiple effects of crop N fertilizer application.

calculated environmental and human health damage costs of crop N fertilization (Cai et al., 2023; Zhang et al., 2016b), they almost did not consider the indirect environmental costs, which are the cost of environmental pollution caused by increased use of chemical pesticides due to increased crop N fertilization.

Wheat is one of the three staple crops along with rice and maize in the world. Excessive N fertilizer application increases wheat grain yield significantly but leads to a large amount of Nr losses, including NH_3 volatilization, direct N_2O emissions and N leaching, and greenhouse gas emissions, including direct and indirect N_2O emissions (Chen et al., 2014; Ju et al., 2009; Liu et al., 2016). Excessive N fertilizer application also increases the occurrences of most wheat insect pests and pathogens (e.g. cereal aphidsand wheat powdery mildew) (Aqueel and Leather, 2011; Luo et al., 2021; Mahfuza and Gordon, 2008). However, few studies have revealed the indirect effects of wheat N fertilizer application triggered by a N-wheat-pest cascade pathway, including the occurrence of pests and the use of chemical pesticides, and then evaluated the impact of this effect on NEEB. In this study, we have considered the crop yield and direct N-related environmental effects of N fertilizer application; more importantly, we have tried to reveal the indirect effects caused by N fertilizer application, the formation pathway of these effects, and the impact of these indirect effects on NEEB, so as to comprehensively understand the multiple effects of crop N fertilizer application. These understandings can help guide the rational application of N fertilizer to crops more accurately to achieve the dual goals of high crop yields and lower environmental pollution, thereby promoting sustainable and intensive agricultural production (Garnett and Godfray, 2014; Tilman et al., 2002; Zhang et al., 2015a).

2. Materials and methods

2.1. Experiment design

This experiment was conducted for three years from 2016 to 2018 in the Yucheng Comprehensive Experimental Station in Dezhou City (36°57′N, 116°36′E), Shandong Province of the North China Plain. This region is a typical temperate semiarid zone with a long history of crop culture. Nowadays, the winter wheat - summer maize rotation system is the main cropping pattern on the North China Plain, where is the largest agricultural production area in China and plays a vital role in ensuring China's food security (He et al., 2011). However, most farmers have applied excessive N fertilizer in wheat fields thus causing serious environmental impacts, such as the leaching of nitrate and emissions of nitrous oxide and ammonia (Chen et al., 2014; Liu et al., 2016). The experimental plot design is shown in Fig. 2. The field was divided into 32 plots (10m × 5m per plot). The plots were hydrologically isolated with partition walls filled with cement. One approximately 2-m guarding row around the experimental plots and three 1-m wide sidewalks were set up between each group of plots. Each year, five N fertilizer treatments, 0, 70, 140, 210, and 280 kg N fertilizer per hectare (N0, N70, N140, N210, and N280) were applied during wheat's whole growth period from 2005 to the present. Each treatment had six replicated plots, except for eight replicated plots in N280 to make the experimental plots a rectangle. N fertilizer type was applied in the form of urea, and half of the total application rate was applied before wheat sowing and another half during the wheat jointing period. A total of 120 kg ha^{-1} P_2O_5 (as Ca$(H_2PO_4)_2$) and 80 kg ha^{-1} K_2O (as K_2SO_4) was applied as the base fertilizer before wheat sowing for each plot. The wheat (*Triticum aestivum* Linn.) variety, Jimai 22, was planted in early October and harvested in early June each year.

2.2. Indirect effects of wheat N fertilizer application

2.2.1. Insect survey

Cereal aphids, including two dominant species *S. avenae* and *R. padi* in these regions (Yang et al., 2019), were investigated in the experimental plots. In each plot, five randomly-selected points were used to sample cereal aphids by visual inspection and 100 wheat tillers were selected for investigation at each point. All plots were sampled two times per year, about once a week from mid-April to late-April during wheat jointing and heading periods when the population of cereal aphids occurred in large numbers. All plots were sampled within a day period to diminish potential stochasticity. Wheat spider mites (*Petrobia latens* and *Penthaleus major*) and lepidoptera larvae (*Helicoverpa armigera*) were the secondary insect pests in these regions (National Agricultural Technology Extension Center, 2016). The occurrences of these two insect pests increases with N fertilizer input (Altieri et al., 2005; Cui et al., 2003). Wheat powdery mildew (*Blumeria graminis*) was the main wheat disease in these regions and the occurrence of wheat powdery mildew increases with N fertilizer input (Guo et al., 2017; Luo et al., 2021). These two secondary insect pests and wheat powdery mildew were surveyed via visual inspection.

Fig. 2. Experimental plot design in the field. The experimental field was divided into 32 plots of 10m × 5m. These plots were arranged treatments with five N fertilizer application rates, 0, 70, 140, 210, and 280 kg N fertilizer per hectare (N0, N70, N140, N210, and N280). Each N fertilizer treatment had six replicates, but the treatment with 280 kg N fertilizer per hectare had eight replicates. About a 2-m guarding row was set up around the experiment plots and a 1-m wide sidewalk was set up between each group of plots.

2.2.2. Pesticide use

During the appropriate period of pest control in the wheat heading periods, we used insecticides and fungicides to control wheat insect pests (cereal aphids *S. avenae* and *R. padi*, spider mites *P.latens* and *P. major*, and lepidoptera larvae *H. armigera*) and wheat powdery mildew (*B. graminis*) according to their occurrences after two samplings of cereal aphids.

2.3. Agronomic and N-related direct environmental effects of wheat N fertilizer application

2.3.1. Agronomic effects of wheat N fertilizer application

At the wheat maturation stage, three samples of 1-m^2 whole wheat plants in each plot were harvested and dried at 60 °C for 72 h, after which the wheat grain yields were determined (Zheng et al., 2019).

2.3.2. Estimation of N-related direct environmental effects of wheat N fertilizer application

For evaluating N-related direct environmental effects of different N rates in wheat plots, the following N environmental indices were calculated:

$$Total\ Nr\ losses = (Nr\text{-}N_2O) + (Nr\text{-}NH_3) + (Nr\text{-}leaching) \quad (1)$$

Nr is the reactive N losses (in kg N ha^{-1}), and *Nr-NH_3* is the NH_3 volatilization Nr loss (in kg N ha^{-1}). *Nr-N_2O* is the direct N_2O emission Nr loss (in kg N ha^{-1}). *Nr-leaching* is the N leaching Nr loss (in kg N ha^{-1}). The estimates of direct N_2O emission, NH_3 volatilization and nitrate leaching in wheat plots at different N rates throughout growing season followed related equations in a previous study (Cui et al., 2014). The total N_2O emission is the sum of direct N_2O (*Nr-N_2O*) and indirect N_2O emissions (equation (2)). Indirect emissions of N_2O from leaching and NH_3 volatilization were estimated as equation (3):

$$Total\ N_2O\ emission = Nr\text{-}N_2O + N_2O_{indirect} \quad (2)$$

$$N_2O_{indirect} = EF_{leaching} \times (Nr\text{-}leaching) + EF_{NH3} \times (Nr\text{-}NH_3) \quad (3)$$

where $N_2O_{indirect}$ is the indirect N_2O emission (in kg N ha^{-1}), $EF_{leaching}$ is the N_2O emission factor for N leaching; and EF_{NH3} is the N_2O emission factor for NH_3–N. More information on the emission factors is provided in Table 1.

2.4. Economic costs, environmental and human health damage costs, and NEEB

The *economic benefit* (equation (4)), $NEEB_N$ (NEEB not considering environmental and human health damage costs of pesticides) (equation (5)), and $NEEB_{NP}$ (NEEB considering environmental and human health damage costs of pesticides) (equation (6)) were determined for different wheat N rates by the following equations:

$$Economic\ benefit = Yield \times Price_w - N \times Price_n - P \times Price_p \quad (4)$$

$$NEEB_N = Yield \times Price_w - N \times Price_n - P \times Price_p - Nr \times Price_{Nr} \quad (5)$$

$$NEEB_{NP} = Yield \times Price_w - N \times Price_n - P \times Price_p - Nr \times Price_{Nr} - P \times Price_{ep} \quad (6)$$

in which *Yield* is the wheat average grain yield of six or eight plots at each N rate (in kg ha^{-1}), *N* is wheat N rate (in kg ha^{-1}), and *P* is the amount of each chemical pesticide (in kg ha^{-1}) at each N rate. $Price_w$, $Price_n$ and $Price_p$ are the price of wheat (in \$ kg^{-1}), N fertilizer input (in \$ kg^{-1} N), and each chemical pesticide (in \$ kg^{-1}), respectively. *Nr* is the total reactive N losses (in kg N ha^{-1}) or its corresponding direct/indirect greenhouse gas (GHG) emissions (in Mg CO_2-eq ha^{-1}) from N_2O, leaching and NH_3 volatilization transformed in reference to IPCC guidelines (IPCC, 2021); $Price_{Nr}$ is the price of Nr costs of acidification, eutrophication, health or GHG trade (in \$ kg^{-1} N or \$ Mg^{-1} CO_2-eq); and $Nr \times Price_{Nr}$ is the environmental and human health damage costs of Nr. $P \times Price_{ep}$ is the environmental and human health damage costs of chemical pesticides. More information on the emission factors and market prices/costs is provided in Table 1. Other operational costs were not included in the cost–benefit analysis, as it was assumed that the agricultural management costs were standardized across treatments at different N rates.

Table 1
Emission factors for indirect N_2O emission, CO_2 equivalent conversion factor, and prices, reactive N costs or pesticide costs.

Category	Emission factor (EF)	Cost or price	Source (factor/price)
Leaching	0.0075 kg N2O–N kg^{-1} N	Health: \$0.21 kg^{-1} N Ecosystem: \$17.17 kg^{-1} N	Paustian et al. (2006); Sobota et al. (2015); Xia et al. (2016).
NH3 volatilization	0.01 kg N2O–N kg^{-1} N	Health: \$1.85 kg^{-1} N Ecosystem: \$1.98 kg^{-1} N	Gu et al. (2012); Paustian et al. (2006); Xia and Yan (2012).
Direct/indirect N2O emission	0.298 Mg CO2-eq kg^{-1} N2O	Greenhouse gas price: \$26.145 Mg^{-1} CO2-eq Health: \$0.3 kg^{-1} N	Gu et al. (2012); van Grinsven et al. (2013);. Myhre et al., 2013.
Pesticide	–	[a]Environmental and health:\$17.99 kg^{-1} active ingredient	Leach and Mumford (2008).
N fertilizer	–	\$0.623 kg^{-1}	China's fertilizer network (http://www.fert.cn/)
Wheat grain	–	\$0.340 kg^{-1}	China's food information network (http://www.grainoil.com.cn)

[a] Estimated environmental and human damage health costs of pesticides referred to England for converted and inflated from 2005 to 2023 figures (refer to British data).

2.5. Statistic analysis

Data of cereal aphids from five N rates in each year or three consecutive years were analyzed statistically using the Shapiro-Wilk test to assess for normality and equal variance test for same variance, followed by one-way ANOVA with the Ducan's post hoc test. A simple linear regression model ($y = a\ x + b$) with a normal error distribution was used to relate the abundance of *S. avenae*, *R. padi*, and the total number of cereal aphids in three consecutive years to five N rates.

3. Results

3.1. Indirect effects of wheat N fertilizer application

In total, we collected 308,100 individual insects, consisting of 189,210 *S. avenae*, 118,890 *R. padi*. From 2016 to 2018, the total abundance of *S. avenae* in treatments with 140, 210, and 280 kg ha^{-1} N rates was higher compared to that in treatments without N application ($F = 8.094$, $P < 0.001$, Fig. 3a). The abundance of *R. padi* and cereal aphids (*R. padi* and *S. avenae*) in 140, 210, and 280 kg ha^{-1} washigher than that in 0 and 70 kg ha^{-1} (*R. padi*, $F = 6.655$, $P < 0.001$, Fig. 3b; cereal aphids, $F = 12.249$, $P < 0.001$, Fig. 3c). Moreover, the increases in the abundance of *R. padi*, *S. avenae,* and cereal aphids from 2016 to 2018 were correlated to a large extent with an increase of N fertilizer input (Fig. 3a–c). For each year, the abundance of *R. padi* and *S. avenae* in 70, 140, 210, and 280 kg ha^{-1} was also higher than that at 0 kg ha^{-1} (Fig. 3d–e).

The occurrences of wheat spider mites (*P. latens* and *P. major*), lepidoptera larvae (*H. armigera*), and wheat powdery mildew in treatment without N application (0 kg ha^{-1}) were very low and obviously lower than treatments with N application (70, 140, 210, and 280 kg ha^{-1}). Thus, no pesticides were used in a treatment without N application (0 kg ha^{-1}). At each year, the pesticide use in wheat fields at different N rates were the same due to the small differences in the occurrences of cereal aphids (Fig. 3a–e) and other secondary pests among different N rates. In total, 0.447 kg of chemical pesticides (0.222 kg insecticides and 0.225 g of fungicides) per year were used to control wheat insect pests (cereal aphids, spider mites, and lepidoptera larvae) and pathogens (powdery mildew) in each treatment of N application, while no pesticides were used in a treatment without N application (0 kg ha^{-1}) (Fig. 3f).

3.2. Agronomic and N-related direct environmental effects of wheat N fertilizer application

The average wheat grain yields in 140, 210, and 280 kg ha^{-1} are higher than 0 and 70 kg ha^{-1}, however, no significant effects of fertilization were found among 140, 210, and 280 kg ha^{-1} (Fig. 4a). The significant effects of fertilization were found between 0 and 70 kg ha^{-1} ($F = 152.6$, $P < 0.001$, Fig. 4a). However, our results showed that the negative N-related direct environmental effects increased with the

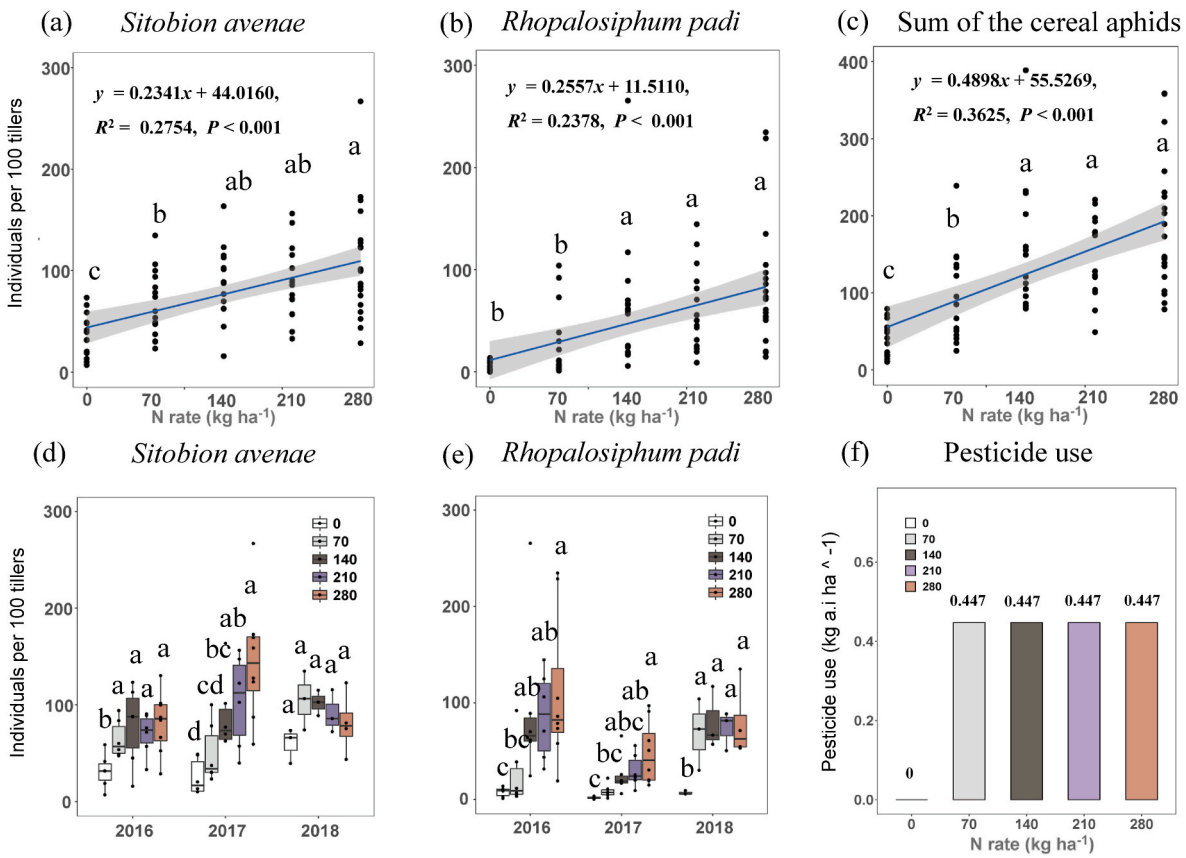

Fig. 3. Indirect effects of wheat N fertilizer application. (a–c) Linear relationships between the abundances of (a) *S. avenae*, $n = 15$, (b) *R. padi*, $n = 15$, (c) the sum of cereal aphids (*S. avenae* and *R. padi*), $n = 15$, and N rates in wheat plots from 2016 to 2018, except for $n = 20$ in treatment with a 280 kg ha^{-1} N rate; (d–e) the abundance of (d) *S. avenae*, n = 6, and (e) *R. padi*, n = 6, at five N rates in wheat plots in each year, except for $n = 8$ in 280 kg ha^{-1} N rate. Each point represents the aphid average abundance per 100 wheat tillers for five sampled points in each plot in two sampling times in each year. (f) the amount of pesticides' use (insecticide and fungicide use) per hectare per year at five N rates. Different lowercase letters indicate a significant difference at the $P < 0.05$ level according one-way ANOVA with the Duncan test.

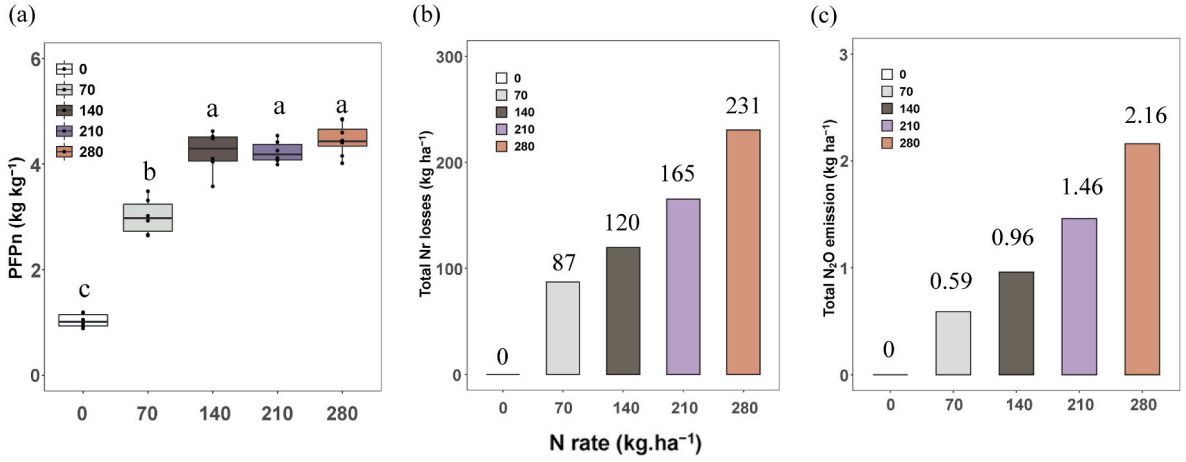

Fig. 4. Agronomic and N-related direct environmental effects of wheat N fertilizer application. (a) The wheat grain yield, (b) total Nr losses, and (c) total N_2O emission at five N rates.

increase of N application. Specifically, estimated total Nr losses and total N_2O emissions in 0, 70, 140, 210, and 280 kg ha^{-1} were 0, 87, 120, 165, and 231 kg ha^{-1} and 0, 0.59, 0.96, 1.46, and 2.16 kg ha^{-1}, respectively (Fig. 4b and c).

3.3. The impact of indirect effects of wheat N fertilizer application on NEEB

The total economic, environmental, and human health damage costs of pesticides and N fertilizer in 0, 70, 140, 210, and 280 kg ha^{-1} increased with an increase of N fertilizer input (Fig. 5a). The total environmental and human health damage costs of pesticides and N

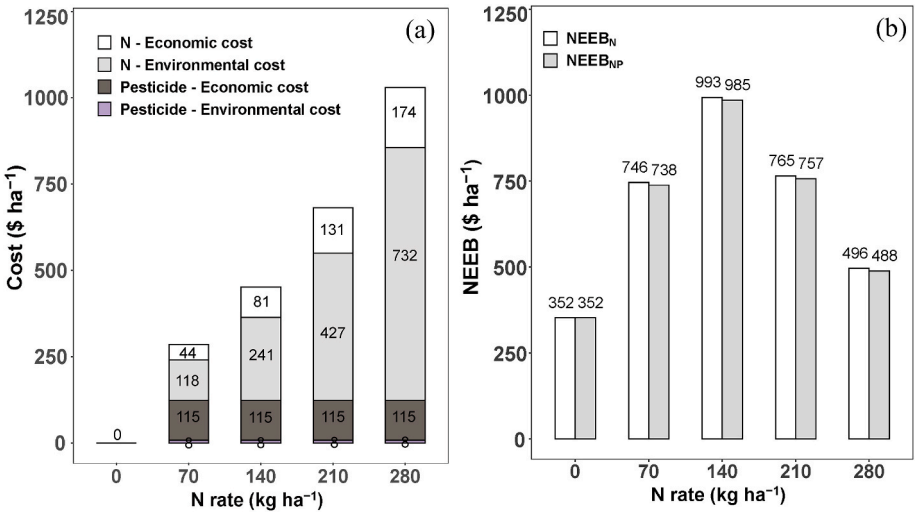

Fig. 5. Economic and environmental costs, NEEB of wheat N fertilizer application. (a) Economic costs of N fertilizer input (N-Economic cost) and pesticides (Pesticide-Economic cost), environmental and human health damage costs of total reactive N (N-Environmental cost) and pesticides (Pesticide-Environmental cost) at wheat five N rates; (b) NEEB not considering environmental and human health damage costs of pesticides ($NEEB_N$), and NEEB considering environmental and health damage costs of pesticides ($NEEB_{NP}$) at five N rates.

fertilizer (including Nr releases and N_2O emissions) in treatments with N application (70, 140, 210, and 280 kg ha^{-1}) increased with N rates and accounted for 44.21%, 54.96%, 63.88% and 71.91% of the total costs in each N treatment, respectively (Fig. 5a). Moreover, the environmental and human health damage costs associated with Nr releases and N_2O emissions were \$0, \$118, \$241, \$427 and \$732 per hectare in 0, 70, 140, 210, and 280 kg ha^{-1}, which accounted for 0, 41.4%, 54.16%, 62.7%, and 71.14% of the total costs in each N treatment, respectively. The economic costs, and environmental and human health damage costs of pesticides (insecticides and fungicides) in treatments with N application (70, 140, 210, and 280 kg ha^{-1}) were \$115 and \$8 per hectare, respectively (Fig. 5a). More importantly, NEEB in each treatment with N application (70, 140, 210 and 280 kg ha^{-1}) considering environmental and human health damage costs of pesticides ($NEEB_{NP}$) is \$8 per hectare lower than NEEB that did not consideri the environmental and human health damage costs of pesticides ($NEEB_N$) (Fig. 5b).

4. Discussion

4.1. Indirect environmental effects of N fertilizer application triggered by the N–crop–pest cascading pathway

Past research has rarely reported on the indirect negative environmental effect of crop N fertilizer application and the formation pathway of this effect. Two species of cereal aphids and wheat powdery mildew are also major insect pests and diseases in the North China Plain where this study was conducted (Guo et al., 2017; Yang et al., 2019). In this region, excessive application of N fertilizer is common on wheat, and the average N fertilizer application rate is 224 kg ha^{-1} (Liu et al., 2016), which has largely led to serious occurrences of cereal aphids and wheat powdery mildew in this region (Luo et al., 2021; Yang et al., 2019), resulting in 0.18 g of pesticides applied for the production of each kilogram of wheat grain in China (Zhang et al., 2016a). In other regions of China or many other countries, it was generally found that a variety of pests on various crops were positively correlated with the amount of N fertilizer applied to the crop, which also showed that excessive N fertilizer application on crops leads to the occurrence of large numbers of pests (Han et al., 2019; Mahfuza and Gordon, 2008; Rashid et al., 2017). As a result, chemical pesticide application are significantly increased in wheat fields that are fertilized with large amounts of N fertilizer compared to wheat fields that are not fertilized with N fertilzier (Fig. 3f). The new pathway revealed in this study may partly explain the positive relationship between N fertilizer application rates and chemical pesticide application rates. Recent studies have reported that insect pests treated with high N fertilzer can accumulate more microorganisms in their intestines, thereby improving their tolerance to pesticides and leading to an increase in the use of chemical pesticides (Hu et al., 2022). This study found that the indirect environmental effect of crop N fertilizer application was triggered by the N–crop–pest cascade pathway. This pathway revealed in this study may be a broader pathway leading to higher chemical pesticide application rates under high N fertilizer treatments for crops. Moreover, the formation pathway of this environmental effect is completely different from the three previously reported environmental effects of crop N fertilzer application (Cui et al., 2014), and is a hidden indirect pathway.

4.2. The impacts of indirect effects of N fertilizer application on NEEB

Net ecosystem economic benefit (NEEB) is usually used to assess the comprehensive economic benefit of crop production based on the benefit of crop yield and the economic, environmental and human health damage costs of agricultural inputs (Cai et al., 2023; Zhou et al., 2019). In this study, wheat yield increased with the increase of N fertilzer application rate under 140 kg ha^{-1}, and then remained basically unchanged (Fig. 4a), which was similar to previous studies (Cerrato and Blackmer, 1990; Liu et al., 2016). Therefore, as the amount of N applied to wheat increases, the relative economic income follows a similar pattern, which is also similar to previous study (Ma et al., 2019). As the amount of N fertilizer application increases, the amount and proportion of direct environmental pollution continues to increase (Fig. 4b and c), indicating that the pollution directly caused by N application is very serious, which is also similar to the results of previously published article (Chen et al., 2014; Cui et al., 2014; Ju et al., 2009). Therefore, both the economic cost and the environmental cost of N fertilizer application increase with the increase in N application rate (Fig. 5a). Since almost no research has revealed that crop N fertilizer application can bring negative environmental effect through N–crop–pest cascade pathway, previous published studies did not include the environmental and health damage costs of pesticides when calculating NEEB (Cai et al., 2023; Zhang et al., 2016b). When considered, the indirect environmental effect of crop N fertilizer application further weakened NEEB, and NEEB at four N fertilizer treatments further decreased (Fig. 5b), indicating that previous studies overestimated NEEB (Cai et al., 2023; Zhang et al., 2016b).

However, in current actual crop production, the environmental costs caused by the use of chemical pesticides should be greater than the values obtained in this study, mainly for the following reasons. First, there is no significant differences in the abundance of cereal aphids at four N rates (70, 140, 210, and 280 kg ha^{-1}) at each year. Therefore, the amounts of chemical pesticides are the same at four N rates, which made the costs of chemical pesticides the same. But, in fact, when farmers sprayed pesticides for control, the more pests they sprayed, the more pesticides they used. Second, the environmental and human health damage costs caused by chemical pesticides in this study were calculated with reference to the unit price of environmental and human health damage costs per kilogram of active ingredients of chemical pesticides in England (Leach and Mumford, 2008; Pretty et al., 2001), while there may be few studies about the data in China. However, the excessive use of chemical pesticides in China is very common, and China ranks among the top in the world in the use of chemical pesticides (Stokstad and Grullón, 2013), which may cause greater environmental and human health damage costs, so calculations with reference to British data are likely to be underestimated. Third, assessing environmental and health issues related to pesticides is made more difficult by the complexity of the problem and the paucity of the data. For example, an acceptable monetary value for the loss of human life or cancer disease caused by pesticides is difficult to estimate and is likely to be underestimated (Pimentel, 2005). Therefore, in real crop production, the NEEB of N application to crops may be seriously overestimated compared with this study.

Excessive N fertilizer application is common in multiple crops in most parts of world and leads to serious N-related direct environmental pollution (Chen et al., 2014; West et al., 2014). This study also confirmed that excessive application of N fertilizer to crops increases the use of chemical pesticides, which makes us even more aware of the necessity and urgency of reducing crop N fertilizer use (Garnett and Godfray, 2014). When calculating NEEB considering and not considering the environmental cost of chemical pesticides, the maximum values were both obtained at 140 kg ha^{-1} (Fig. 5b), which may be due to the fact that only five N fertilization treatments were set up. If data on a large number of farmers' fields are studied regionally or nationwide, the amount of N fertilizer that achieves the greatest economic benefit by considering the environmental costs of chemical pesticides should be significantly lower than without considering the environmental costs of chemical pesticides. Therefore, compared with previous studies (Cui et al., 2014; Liu et al., 2016; Wang et al., 2017), the amount of N fertilizer applied to wheat needs to be further reduced to achieve the greatest ecological and economic benefits, and improve agricultural sustainability.

5. Conclusion

A comprehensive understanding of the multiple effects of crop N fertilizer application will help us to more accurately formulate solutions to reduce N fertilizer use to achieve high crop yields and reduce environmental pollution, which is essential to realize sustainable crop production (Garnett and Godfray, 2014; Tilman et al., 2002). The agronomic effects (yield and N use efficiency) and N-related direct environmental effects of crop N fertilizer application have been widely studied (Cassman et al., 1998; Frank and Dirk, 2005; Wang et al., 2017). However, nearly none studies have considered the indirect environmental effect of N fertilizer application owing to so much pesticide use being triggered via a N-crop-pest cascade pathway and the impact of this indirect effect on NEEB.

In this study, we reveal a new pathway through which crop N fertilizer application can indirectly bring about a negative environmental effect, namely the N-crop-pest cascade pathway. Excessive N fertilizer application on crops enhances this cascade pathway, thereby indirectly increasing the use of chemical pesticides and causing negative environmental effects that further weaken NEEB. Our study extends previous studies and contributes to a more comprehensive understanding of the environmental effects of N fertilizer application on crop, as well as a re-evaluation of the ecological and economic benefits of these application more accurately. China's crop production faces the dual challenges of excessive N fertilizer application and excessive chemical pesticide use (Chen et al., 2014; Stokstad and Grullón, 2013). This study provides knowledge that supports a policy formulation to reduce crop N fertilizer application in order to achieve maximum ecological and economic benefits, thereby improving the sustainability of agriculture.

However, this study is a controlled experiment at the plot scale. The scale of this study is small and the pesticides are used scientifically based on the crop damage caused by the pests. In actual situations, many farmers lack the knowledge of scientific pesticide use and spray pesticides whenever they see insects. The more pests there are, the more pesticides are sprayed on them (Chèze et al., 2020; unpublished survey data), which makes it likely that the amounts of chemical pesticides used by farmers is much higher than the amount used in this study (Zhang et al., 2016a). Therefore, future research can construct regional, national, or even global scale databases to more comprehensively and realistically assess the current status of chemical pesticide use caused by crop N fertilization and the resulting impact on the ecological benefit of the ecosystem. In addition, future research can also combine machine learning modeling methods to predict the environmental effects of crop N fertilizer application at different spatial scales (Ghasemi-Mobtaker et al., 2022; Nabavi-Pelesaraei et al., 2021) or use multi-objective optimization algorithms to estimate the appropriate amount of crop N fertilizer to achieve high crop yields while reducing direct and indirect negative environmental effects (Saeidi et al., 2022).

CRediT authorship contribution statement

Quanfeng Yang: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Investigation. **Junhua Ma:** Data curation, Writing – original draft, Visualization, Investigation, Writing – review & editing. **Fei Yang:** Visualization, Investigation. **Hua Zheng:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Supervision, Writing – review & editing. **Zengbin Lu:** Visualization, Investigation. **Fei Qiao:** Visualization, Investigation. **Kening Zhang:** Visualization, Investigation. **Huarui Gong:** Visualization, Investigation. **Xingyuan Men:** Visualization, Investigation. **Jing Li:** Data curation, Writing – original draft, Supervision, Writing – review & editing. **Fang Ouyang:** Data curation, Writing – original draft, Supervision, Writing – review & editing. **Feng Ge:** Data curation, Writing – original draft, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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